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ELEGAS: GASEOUS ELECTRICAL INSULATION

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/Figures are appended./

We will consider in this article the properties of gaseous insulation and the possible utilization of gases with high electrical strength. Not only is the fitness of a certain gas as insulation determined by high rupture strength, but the gas must also possess other favorable physical and chemical properties. As will be demonstrated, sulfur hexafluoride, provisionally called elegas, is the most suitable gas for electrical insulation. We will describe our experiments on the use of elegas in heavy-duty hf condensers of both constant and variable capacity. As a result, we can recommend elegas for high-voltage uses (gas-filled cables, high-potential electrostatic generators, etc.).

At present compressed-gas insulation has assumed very great importance. Negligible conductivity and the virtual absence of dielectric losses are the advantages of gaseous insulation; however, the low electric strength (under usual conditions) vitiates the use of gases as insulation. The gases ordinarily employed for this purpose (air, nitrogen, or carbon dioxide) possess almost identical electrical strengths: approximately 30 kv/cm at atmospheric pressure. Unfortunately, this strength is considerably less than the rupture strength of liquid or solid insulators.

In many cases, therefore, gaseous insulation naturally should not be used, in spite of its otherwise good properties: negligible conductivity and losses. The rupture strength of gaseous insulation has ordinarily been increased through increasing the pressure. In a uniform electrical field the rupture voltage increases linearly with pressure within limits of up to several tens of atmospheres. In a nonuniform field, however, the rupture voltage begins to grow more slowly as pressure is increased, and as the field becomes less and less uniform the rupture voltage begins to increase more and more slowly at lower pressures. This fact must be noted in any practical utilization of gaseous insulation, since under actual conditions the field is always nonuniform to a greater or lesser degree. Under these conditions of nonhomogeneity the higher the rupture voltage obtained by compression of the gas, the

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less effective any subsequent increase of pressure. In connection with the fact that increasing the pressure usually introduces great complications, relative to the construction of seals, outputs, etc., excessively high pressures should not be sought; certain optimum pressures which are most suitable for each particular case should be found in a rational manner.

The rupture strength of gaseous insulation can be increased not only by increasing the pressure, but also by employing gases with greater electrical strength, thus significantly lowering the gas pressure necessary for the same operating voltage or permitting a higher voltage to be attained at the same pressure.

Electrical Strengths of Various Gases

As early as 1889 Natterer (1), studying the electrical strength of many gases and vapors, discovered that certain of them possessed greater strengths. Unfortunately, Natterer's data did not permit determination of the breakdown field intensity, since all his measurements were concerned with sharply nonuniform electric fields. More recently a series of new works has appeared: Charlton and Cooper (2) investigated about 80 different vapors and gases; unfortunately, however, they studied only a few of these in the pure form, i.e., they studied in a mixture with air those which do not produce at normal temperature a vapor tension as high as 1 atm). Kovalenko (3) investigated the rupture strength of a number of vapors and gases at the Physics Institute /imeni P. N. Lebedev/, Academy of Sciences USSR, in B. M. Vul's laboratory.

With Glikina and Bonch-Bruyevich (4), and later with Zandberg (5), the author studied the rupture voltages of a large number of vapors and gases at the Leningrad Physicotechnical Institute, Academy of Sciences USSR.

Table 1 shows the comparative rupture values of the gases studied (relative to the rupture strength of nitrogen or air).

Table 1. Relative Rupture Strengths of Various Gases

Substance	CCl_4	SeF_6	CCl_3F	CCl_3H	C_2H_5I	C_3H_3I	$C_2Cl_2F_2$
Comparative electrical strength	6.3	4.5	3-4.4	4.3	3.0	2.9	2.8
Bp (° C)	76	49.2*	24.1	61	72	42.8	38

Substance	SF_6	SOF_2	CCl_2F_2	SO_2	C_6H_{14}	C_6H_{12}	C_2H_5Br
Comparative electrical strength	2.3-2.5	2.5	2.4-2.5	1.9-2.3	2.1	1.7	1.5
Bp (° C)	-62*	-30	-28	-10	49	36	38

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Substance	C_2H_5Cl	CF_4	N_2	CO_2
Relative electrical strength	1.25	1.1	1.0	0.9
Bp (° C)	13	-126	-195.8	-78.5*

* The tension of the saturated vapors over the solid substance at this temperature is 760 mm Hg.

A comparison of the rupture strengths of various gases permitted us to set up a qualitative rule: generally, gases with high molecular weights have high electrical strength, and gases with low molecular weights have low strength.

In studying the rupture strength of gases, we could not be satisfied with this empirical dependence, and we endeavored to clarify the basic principles which govern the rupture strength of gases.

With Zandberg (6), the author investigated predischarge currents in various gases, and from these measurements we determined the coefficients of ionization by electron collision (α is the first Townsend coefficient). From our data we were able to conclude the following: in all gases rupture begins on the application of a field for which the coefficient α reaches a certain value (the same for various gases). At this value of α, a considerable space charge is formed, whose growth leads to the rupture. In some gases this value α is reached for comparatively low electric fields; in others, for higher fields. Thus, we assume that the rupture of a gas is determined basically by the quantity α, while the rupture strength is determined by the growth of this coefficient with the electrical field. This result seems to us extremely important and interesting.

There now remains the still unanswered question of what exactly retards the growth of α in electrically strong gases. We are going to study this problem in the near future.

Demands Made on Gaseous Insulation

For the practical utilization of gases with high electrical strength it is not enough that their strength should merely be greater than that of air, nitrogen, or carbon dioxide. Besides increased resistance, the gas must possess still other favorable physical and chemical properties, the chief ones being as follows:

1. Chemical inertness of the gas to materials found in its atmosphere.

2. Low liquefaction temperature, permitting considerable pressures to be obtained at normal temperatures.

3. Weak decomposition in an electrical discharge.

All these conditions sharply limit the possible choices among gaseous compounds with high electrical strength.

Most compounds which possess high electrical strength in the gaseous state are liquids at ordinary temperatures, or else they are gaseous but too easily liquefied by moderate compression.

For example, gaseous carbon tetrachloride possesses the best (of the gases known to us) relative rupture strength (6.3 times greater than air) at normal temperatures; at normal temperatures, however, CCl_4 is liquid and shows a saturated

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vapor pressure of only 1 atm. In air at atmospheric pressure the addition of saturated CCl_4 vapor increases the rupture voltage 2-2.5 times (depending on the degree of nonuniformity of the field; in a nonuniform field the effect of CCl_4 vapor is greater than in a uniform one). When the pressure of the air is increased the relative effect of CCl_4 vapor decreases; also, unfortunately, in an electrical discharge CCl_4 decomposes readily with the liberation of noxious chlorine. Moreover, if the discharge takes place in a mixture of air and CCl_4, then, as a result of oxidation, a certain amount of poisonous phosgene is obtained. These properties of carbon tetrachloride demonstrate that, despite its exceptionally high electrical strength, it cannot be given wide practical application as gaseous insulation.

The compound CCl_2F_2, called freon (because of its wide use in the refrigerating industry), possesses much more favorable properties. The electrical strength of freon is 2.5 times greater than that of air. The bp of freon is -28° C; at normal temperatures freon can be compressed to several atmospheres. In addition, freon possesses considerable chemical stability, which has favored its use in refrigerators. It is true that copper which has stood for a long time in a freon atmosphere seems to be affected by freon on its surface. As we can see, freon possesses quite favorable properties and can be used as gaseous insulation in those high-voltage installations where there is no danger of a considerable pressure loss and where pressures do not exceed several atmospheres.

Elegas

At the Leningrad Physicotechnical Institute, Academy of Sciences USSR, we attempted not only to investigate the principles governing high electrical strengths in gases, but also to find a gas that would possess both high strength and other favorable properties.

From the large number of compounds investigated (a part of this data is cited in Table 1) we singled out in particular sulfur hexafluoride. The good chemical and physical properties of sulfur hexafluoride suggested its use as gaseous insulation.

The electrical strength of sulfur hexafluoride SF_6 is almost 2.5 times that of air.

Because of its especially favorable properties for high-voltage uses in the electrical industry, we have provisionally given sulfur hexafluoride the name "elegas."

The basic properties of elegas are as follows: At -62° C its vapor tension over solid elegas equals 760 mm Hg; at -50.8° C elegas boils at a saturated vapor pressure of 1,710 mm Hg; at room temperatures its vapor tension reaches several tens of atmospheres; its critical temperature is +54° C. Pure elegas is odorless and harmless and does not burn, and it is stable up to 800° when heated.

Sulfur hexafluoride is an extremely inert compound. Acids, alkalies, (even molten) or water cannot decompose it. Halogens, hydrogen, oxygen, phosphorus, arsenic, selenium, carbon, copper, silver, and other elements do not act on SF_6 even on heating. Calcium and magnesium at red heat do decompose SF_6, but the reaction soon stops because of the formation of scale on the metallic surface. Sulfur does not act on SF_6 even at the melting point; superheated sulfur vapors act on SF_6, producing the lower fluorides. Hydrogen and oxygen act on SF_6 only in a strong discharge (as should be noted, under these conditions oxygen decomposes SF_6, thus leading to the formation of sulfur oxyfluorides, which possess high electrical strength, but unfavorable chemical properties).

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As an example of the chemical inertness of SF_6, medical science has used this gas in pneumothorax.

Figure 1 gives the data characterizing the dependence of the rupture voltage of nitrogen and elegas on pressure (for a uniform field). As is evident, the same rupture voltage in elegas is attained at pressures 2.5 times less than in nitrogen. A still greater advantage is shown under actual practical conditions, when there is a nonuniform field. In this case the pressure can be decreased still more, to give the same protection as that of air, under the conditions of a uniform field. Figure 2 cites the data for spark-over between plates whose edges had a radius of curvature of 2.5 mm when there was a gap of 3.8 mm. As the figure clearly shows, if a voltage of 48 kv is to be obtained nitrogen must have a pressure of 9 kg/sq cm, while elegas needs only 3 kg/sq cm.

Thus, elegas possesses increased electrical strength, allows greater pressures to be obtained, and is in addition one of the most inert and stable chemical compounds. The enumerated properties of elegas should, we feel, guarantee its wide use in practice.

High-Voltage Gas-Filled Condensers

Compressed gas in precision high-voltage condensers has been widely used in practice. The absence of dielectric losses opens large perspectives for the use of condensers with gaseous insulation in hf technology. In the US, condensers with gaseous insulation under pressure are being used and widely advertised; these condensers with capacitance up to 1,500-2,000 mm fd have been rated at 30-40 kv when filled with nitrogen to 25-40 atm.

The use of elegas as insulation has facilitated considerably the operation of powerful high-voltage condensers in hf technology. Glikina, Reynov, and the author (7) developed and constructed industrial models of condensers with capacitance of 300, 600, 1,200, 2,400, and 4,000 mm fd. These condensers can operate continuously at 40-kv peak voltage and $1.2 \cdot 10^6$ frequencies.

A diagram of the condenser is shown in Figure 3.

The high-voltage outlet is made of glass and has a convenient shape (hemispheric) for operation under compression: the outlet consists of two hemispheres (No 1 in figure), of which one (the lower) is working and takes the whole load from the pressure of gas inside the condenser, and the other (the upper) serves only as a support to hold the output bar (2).

The condenser is composed of a set of aluminum disks, one series of which is attached with the aid of the three rods (3) to the lid; and the other set of plates is attached to the bar (2).

The condenser containers were manufactured from seamless pipe with welded flanges for the fastening of the lid. The bottom of the container was carefully welded. To fill the condenser with gas, a special cut-off valve was placed in the side surface of the container. The casing of the valve was so constructed that a manometer could be placed in it which would show the gas pressure in the condenser.

The construction of the high-voltage outlet described and the good hermetical sealing of the container and all packings guaranteed a constant gas pressure for several months (without supplementary addition of gas).

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The industrial models were tested when the condensers were filled with nitrogen and with elegas. When the condensers were filled with nitrogen at pressures up to 15-20 atm, spark-overs appeared even at 35-40 kv peak voltage; but these same condensers would operate continuously and stably at 40 kv when filled with elegas at a pressure of only 8 atm.

The advantage of gaseous insulation is clearly shown at high loads. Thus for example, when lengthy tests were conducted with an elegas-filled condenser of 1,200 mm fd capacitance at a load approaching 2,000 kva, the temperature of the condenser without forced cooling remained at 70° C (for an ambient temperature of 20° C).

On the basis of the experience gained in building and testing the industrial models, one of the Leningrad factories jointly with the Leningrad Physicotechnical Institute designed a number of gas-filled condensers for a new powerful radio transmitting station. During the war, these condensers were manufactured and installed. Unfortunately, as a result of wartime conditions elegas could not be obtained, and therefore the condensers had to be filled with nitrogen (hence at correspondingly higher pressurs; the condensers were designed with a mechanical strength sufficient to allow for use of nitrogen if elegas could not be obtained).

The operation of a large number of these condensers (even under more difficult conditions, i.e., with nitrogen at increased pressure instead of elegas) has shown that gas-filled condensers have been completely efficient and quite reliable.

In addition to condensers of constant capacity, Reynov and the author (8) designed and built a variable condenser containing elegas under pressure. A special device for sealing the rotating assembly provided for the hermetical sealing of the condenser container. In the course of several months, after continuous movement of the rotating system, the gas pressure fell off only a few percent. This condenser permitted almost a tenfold variation of capacitance (from 150 to 1270 mm fd). During continuous tests at a high frequency (wave length 500 m) for 100% modulation and peak voltage 32,000 v no spark-over was observed. At high loads of about 1,000 kva without forced cooling, the steady-state temperature of the condenser exceeded ambient temperature by only 25-35° C.

At present, hf installations have come into extremely wide use in the most diverse branches of industry (as well as the radio engineering). In the case of practical applications of hf currents in factories we may cite melting of metal, casehardening heating, heating and drying of wood, etc. However, our electrical industry is lagging in the output of hf generators, since the problem of providing the most important component part of a hf installation -- the condensers -- is not progressing well. Up to now these condensers have been manufactured from scarce mica or ceramics. We consider that it is now necessary to switch to gas-filled condensers and utilize in their design all those advantages which the use of elegas can offer. We must hope that our chemical industry can in the very near future raise the output of elegas to provide for the needs of the electrical industry.

<u>Opportunities for Use of Elegas in Other High-Voltage Installations</u>

1. Gas-Filled Cables

In the cable industry great difficulties are encountered in the designing and building of high-voltage cables and oil-impregnated insulation. These difficulties reduce to the following points:

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a. Under changing temperature conditions gas bubbles form in the oil-impregnated paper insulation of a cable. The electrical strength of the gas bubbles is less than that of oil, and they become foci for corona discharges, leading to the destruction of the paper foundation and finally to the breakdown of the cable.

b. For liquid impregnation when there is a vertical spacer in the cable great difficulties appear in connection with hydrostatic pressure. These difficulties are eliminated if compressed gas is used instead of oil.

The utilization of gases with high electrical strength as insulation in gas-filled cable appears exceptionally promising.

Preliminary investigations of the rupture strength of cable-type paper in an elegas atmosphere which were conducted by Glikina and the author (9) showed that the use of elegas in place of nitrogen increased the rupture strength almost twofold (see Figure 4). The rupture voltage of paperin elegas at 10 atm approaches the strength of the same paper impregnated with oil.

Preliminary experiments were conducted jointly with the "Sevkabel'" factory for determining the electrical strength of a 10-kv cable with impregnated and dry insulation, which was subsequently filled with elegas. The strength was approximately twice as high as when filled with carbon dioxide or nitrogen.

2. High-Voltage Electrostatic Generators

One method of obtaining superhigh voltages is provided by Van de Graaff electrostatic generators. Without describing the different types of these generators in detail we will list only the basic elements of their design and the role of the surrounding gas medium as insulation.

A charge of low initial voltage is supplied to the "transporter" (an endless belt or disk of insulating material). From the opposite end of the revolving belt, when it passes inside the conducting housing, the charge is removed and charges the conductor. The upper limit to the voltage which can be developed by the generator is determined by the magnitude of the electric field at the surface of the conductor, and the increase of potential is limited by the field intensity's reaching the rupture voltage of the surrounding medium, as well as by the discharge along the belt which carries the charge.

For example, the maximum calculated potential for a spherical conductor of 1 m diameter is equal to 1,500,000 v (assuming that the conductor is located in air at 1 atm, with rupture strength 30,000 v/cm). However, as a result of the non-uniformity of the surface of the conductor and the distortion of the electrical field in the presence of surrounding objects, the actual attainable voltage is considerably less than the voltage as calculated.

Joliot (10) in France was one of the first to use gases with high electrical strength in work with electrostatic generators. Working with a comparatively small generator model which produced a voltage of about 650 kv, Joliot vaporized about one liter of CCl_4 in the chamber (total volume 300 cu m), which resulted in an increase of the voltage developed by the generator to 1,000 kv. However, this method can hardly be considered efficient.

Significant results have been achieved by investigations of the construction of generators which operate in a closed high-pressure chamber. In this field gases with high electrical strength offer great possibilities. Thus, for example, Trump and Van de Graaff (11) built a compact generator for use in X-ray therapy. When filled with air at 11 atm the generator developed voltages up to 1,400 kv. When air was replaced by pure freon (CCl_2F_2) at a pressure of 3.5 atm the voltage reached 1,500 kv. It obviously facilitates the design to use electrically strong gases which permits a decrease in pressure or size.

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Use of gases with high electrical strength, principally elegas, is not limited to the examples listed above. For example, it is possible to use elegas in the hf machines of Academician N. D. Papaleksi.

Unfortunately, the present great delay in the industrial production of elegas has not permitted its wide use. It can be asserted, however, that in the near future elegas will be used extensively in technology.

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[See figures on following page.]

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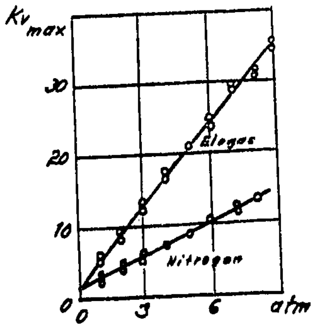

Figure 1. Rupture Voltage and Pressure for a Uniform Field

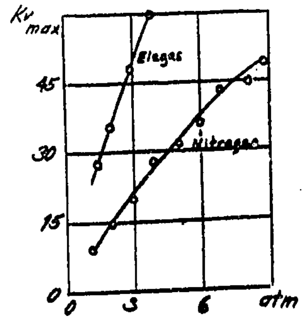

Figure 2. Rupture Voltage and Pressure for a Nonuniform Field

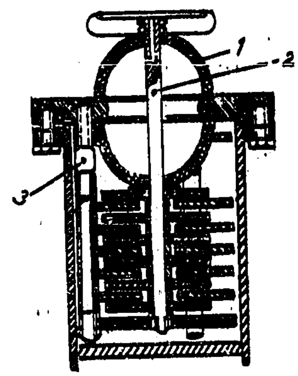

Figure 3. Diagram of Gas-Filled Condenser

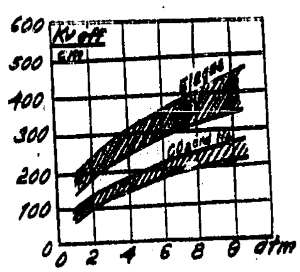

Figure 4. Comparison of Performance of Elegas With CO_2 and N_2

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